



Superelastic Ball Bearings: Materials and Design to Avoid Mounting and Dismounting Brinell Damage in an Inaccessible Press-fit Application-Part II Detailed Analysis

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Superelastic Bearing: Taking Advantage of NiTi Characteristics.

- **Background:**

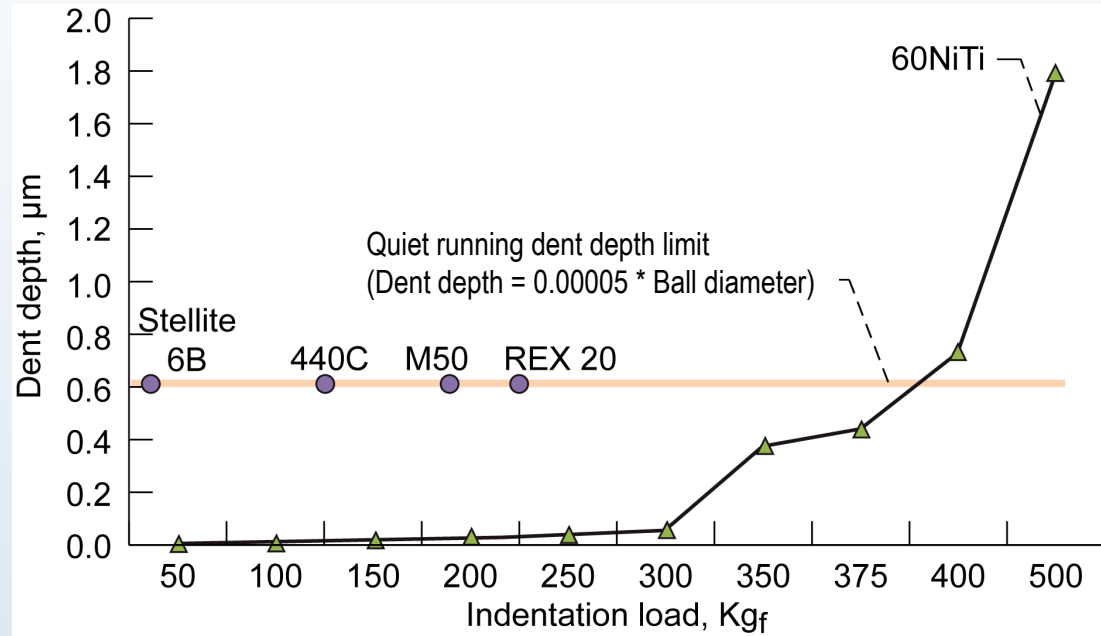
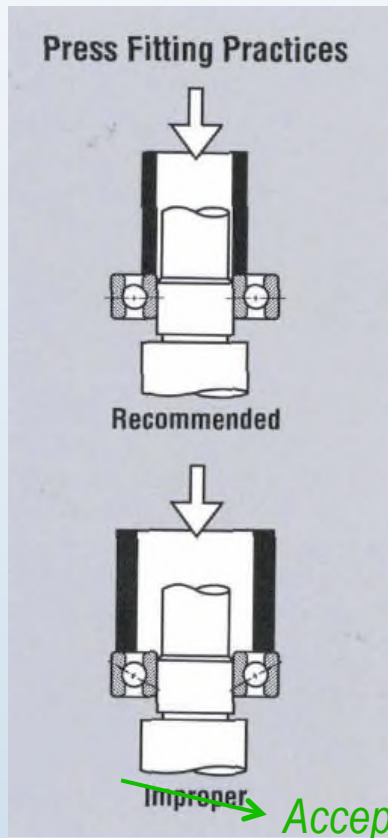
- International Space Station (ISS) Distillation Assembly (DA) Compressor utilizes 12.7 mm (R8) bearings.
- Corrosive environment has not been a life limiting factor, but is a concern to program management.
- Assembly/disassembly process requires pressing the bearings off the rotor through the rolling elements, with an axial force as high as 2.2 kN, resulting in large quantity of scrapped bearings.

- **Premise:**

- Can the benefits of 60NiTi (superelasticity, high hardness, lower modulus, and corrosion resistance) be brought to bear to eliminate the corrosion concerns while enabling damage free assembly/disassembly for bearing reuse?



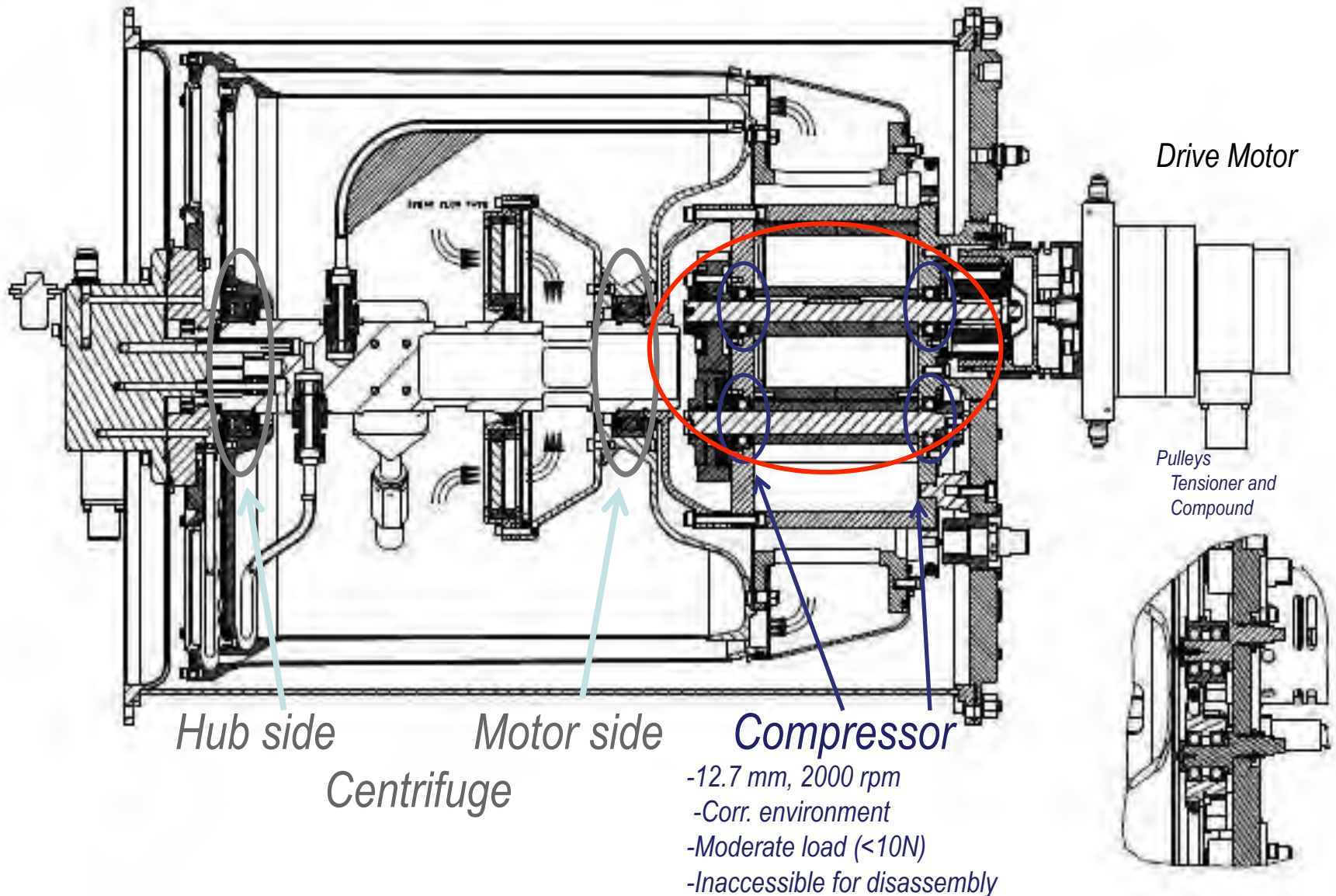
Superelastic Bearing: Taking Advantage of NiTi Characteristics.



- 60NiTi has more load capability for given geometry:
 - Can we utilize that capability to make an “improper” assembly technique “acceptable”?
 - Preliminary analysis is inconclusive due to limited fidelity, simple contact model.



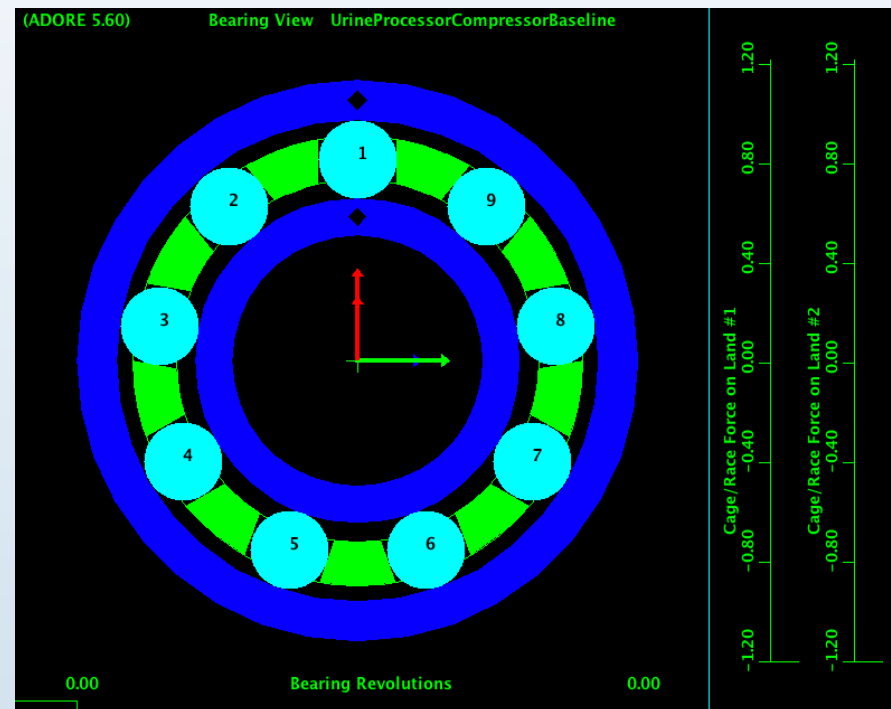
Design a removable R8 compressor bearing for ISS Distillation Assembly





Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

- **Advanced Dynamics Of Rolling Elements (ADORE)**
 - Rigid Body Dynamics analysis tool specifically for rolling element bearings.
 - Uses a Hertz contact model to calculate stress and local elastic deformation in the ball-to-race contacts.
 - Does not include material plasticity, fracture, or global deformations intrinsically.



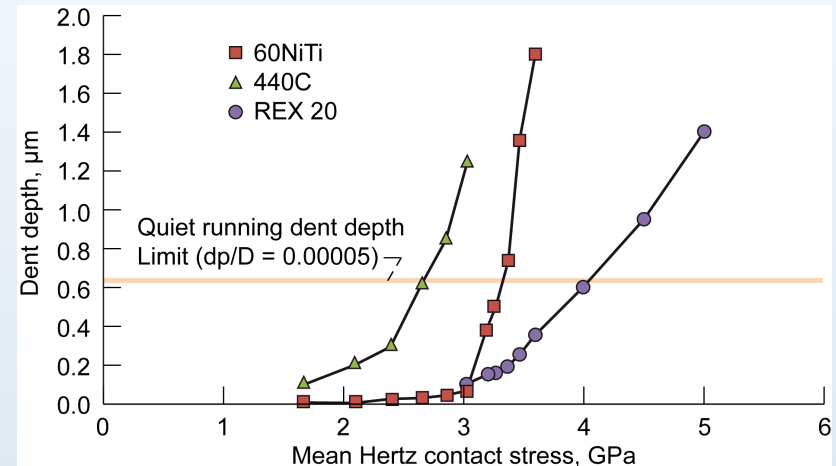
Sample ADORE output for kinematics visualization.



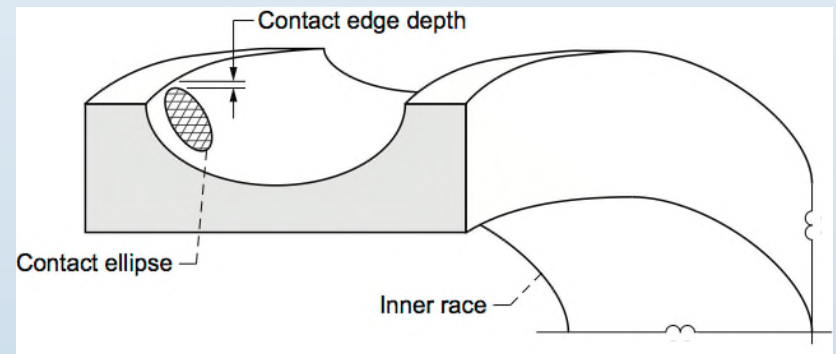
Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

Criteria for Bearing survival of pressing on/off rotor:

- Do not exceed maximum contact stress for smooth running dent.
~2.5 – 4.0 GPa, depending on material.
- Prevent rolling elements from riding over the edge of the race lands.
 - Some extension of the contact ellipse past the edge may be acceptable.
- Ensure material does not fracture.
 - Maximum strain < fracture strain.



Contact stress limit for acceptable dent size.



Contact ellipse relative to the edge of the race groove.

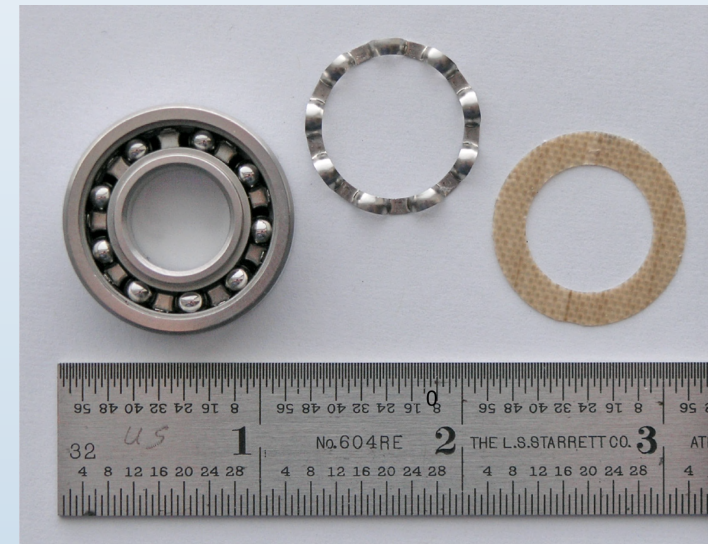


Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

Existing 12.7 mm bearing analysis using ADORE:

- **Contact Stress Criteria:**
 - Static axial load capacity of the bearing is 1.0 kN per manufacturer catalog.
 - The maximum contact stress allowable for the existing bearing (440C Stainless Steel) is 2.5 GPa.
 - 0.6 kN axial force generates 2.5 GPa contact stress – 2.2 kN exceeds capability.
- **Contact Edge Depth Criteria:**
 - ADORE predicts that an axial load of 1.8 kN results in the contact ellipse just reaching the edge of the race groove.

Existing 12.7 mm bearing does not satisfy the criteria!



Partially disassembled 12.7mm
SS compressor bearing



Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

Modified 12.7 mm bearing analysis using ADORE:

- Switch material to 60NiTi, realize following benefits:
 - 60 NiTi has higher allowable contact stress and better corrosion resistance than 440C stainless steel.
 - 60NiTi has lower modulus for better load distribution/lower stress.
 - 60NiTi is harder than superalloys for better wear resistance.
- ADORE calculated contact stress for modified bearing:
 - Outer race contact stress = 2.2 GPa.
 - Inner race contact stress = 2.4 GPa.

Allowable contact stress = 3.1 GPa

RE	...Orbital Position (deg)Contact Angle.... (deg)Contact Load..... (lbf)Contact Stress.... (psi)	...Major Half Width... (in)	..Minor Half Width... (in)					
		Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race
1	4.923E+01	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
2	8.923E+01	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
3	1.292E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
4	1.692E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
5	2.092E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
6	2.492E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
7	2.892E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
8	3.292E+02	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03
9	9.234E+00	3.425E+01	3.425E+01	9.872E+01	9.871E+01	3.250E+05	3.434E+05	2.974E-02	3.634E-02	4.877E-03	3.777E-03

325,000 psi = 2.2 GP

343,000 psi = 2.4 GP

325,000 psi = 2.2 GPa

343,000 psi = 2.4 GPa

ADORE output

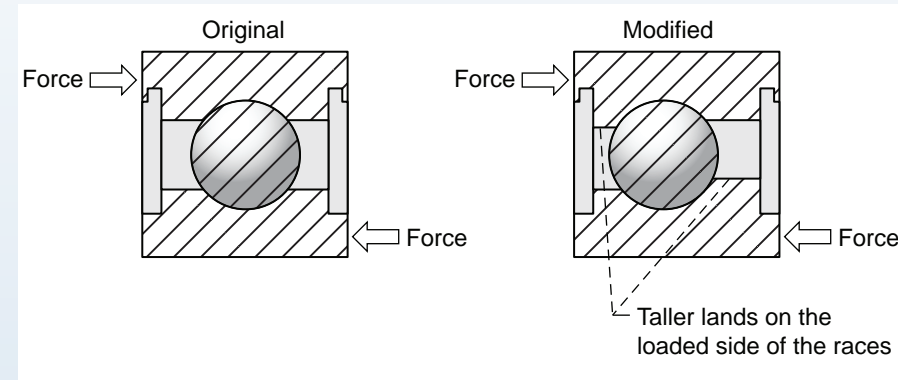


Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

Modified 12.7 mm bearing analysis using ADORE:

- **Modify the race geometry to increase the contact ellipse depth.**
 - Outer race land height is increased by 0.254 mm.
 - Inner race land height is increased by 0.406 mm.
- **Modify the race geometry to increase the contact ellipse depth.**
 - Outer race depth from shoulder = $1.78\text{E-}2$ mm.
 - Inner race depth from shoulder = $2.73\text{E-}3$ mm.

Modified 12.7 mm bearing does satisfy the criteria!



Comparison of original geometry to modified geometry

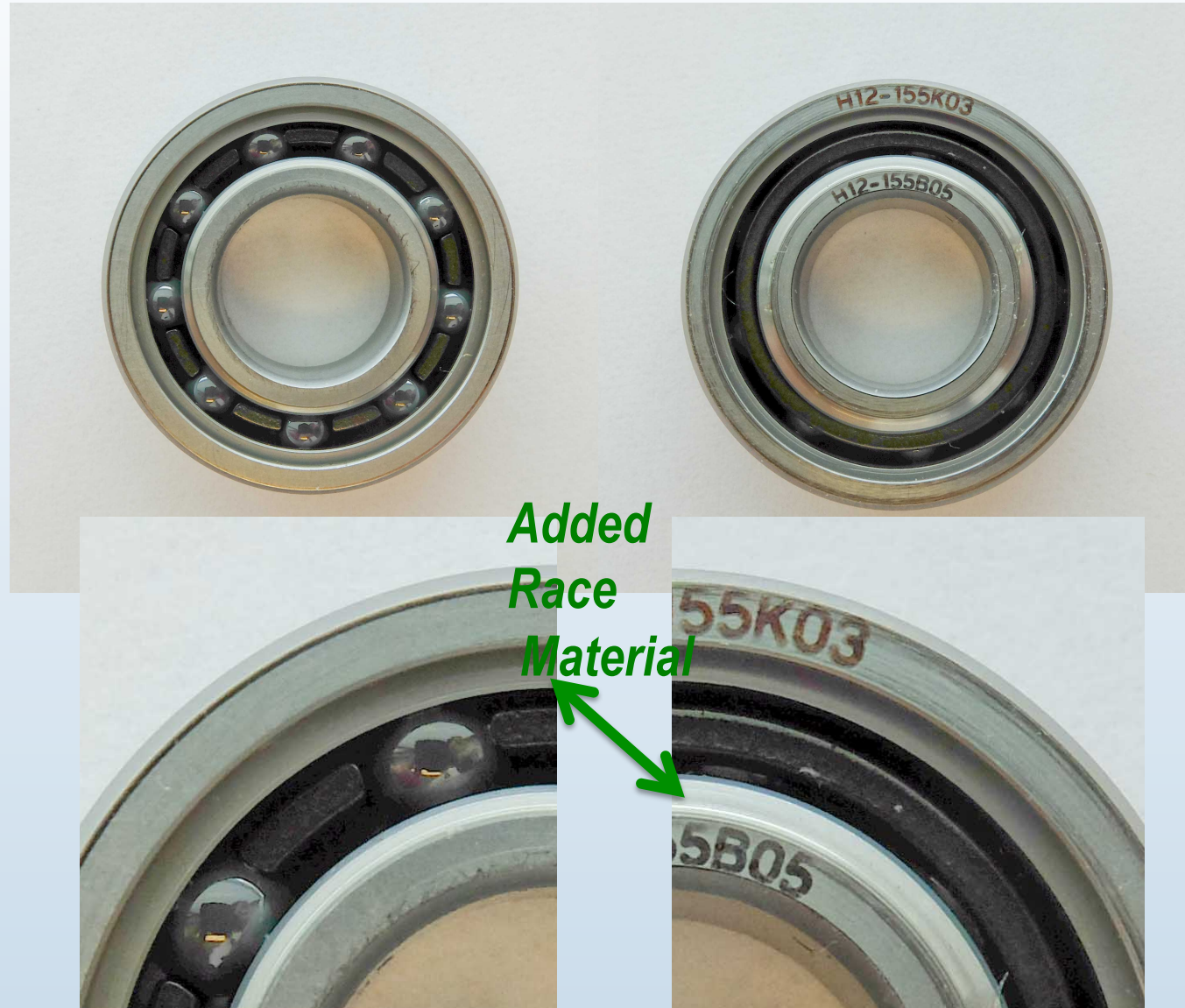
RE .Outer Contact Edge..			7.04E-4 in = 1.78E-2 mm 1.08E-4 in = 2.73E-3 mm
Depth from Shoulder (in)			
Outer Race Inner Race			
1	7.036E-04	1.075E-04	
2	7.036E-04	1.075E-04	
3	7.036E-04	1.075E-04	
4	7.036E-04	1.075E-04	
5	7.036E-04	1.075E-04	
6	7.036E-04	1.075E-04	
7	7.036E-04	1.075E-04	
8	7.036E-04	1.075E-04	
9	7.036E-04	1.075E-04	

ADORE output



Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

- The resulting modified bearing was manufactured.

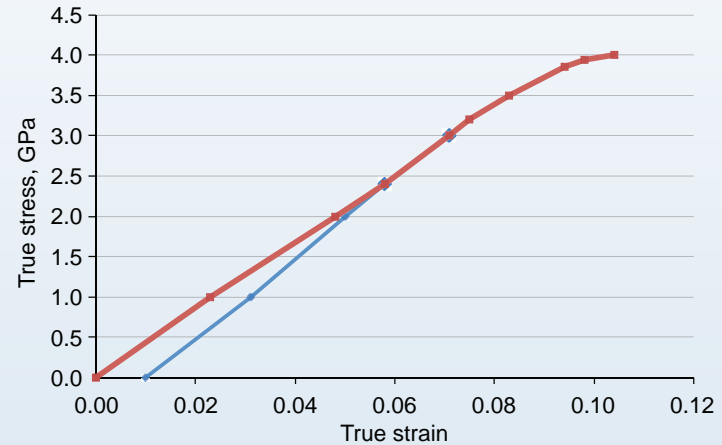




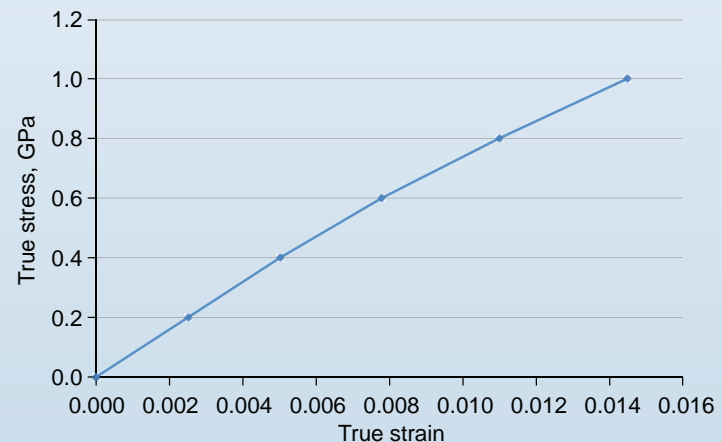
Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

60NiTi Mechanical Properties are atypical:

- While the manufacturing was underway, more detailed analysis was undertaken:
- Fidelity of ADORE analysis insufficient to capture material non-isotropy, plasticity, and somewhat brittle failure mechanism.
 - LS DYNA is well-suited to model these effects.
- Also concerned about material fracture due to local stress/strain maxima.



Compression stress-strain behavior



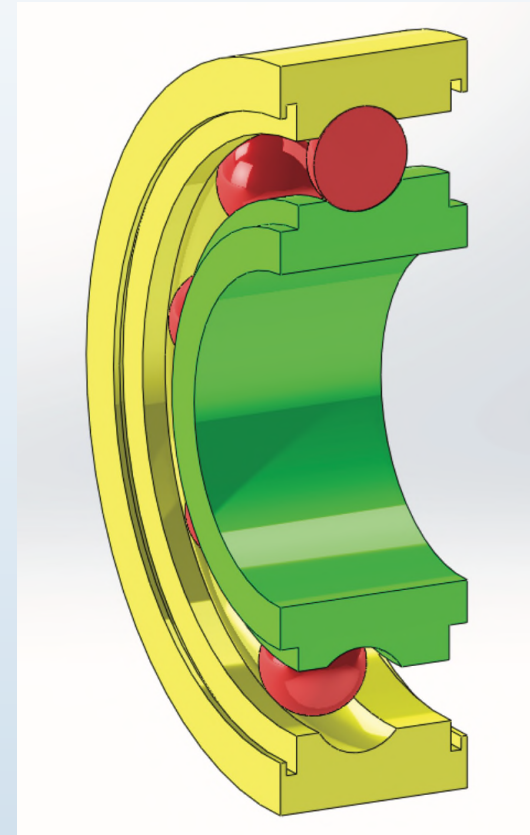
Tension stress-strain behavior



Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

Modified bearing analyzed using LS DYNA:

- **LS DYNA capabilities:**
 - Can model elastic/plastic behavior.
 - Can model different tension and compression behavior.
 - Can include material fracture.
 - Loads and deformations are calculated globally, not only in the contact region.
 - Rather than using the Hertz contact model, a contact algorithm at the nodal scale is used to calculate the contact forces and resulting strain (deformation) in the ball to race contacts.



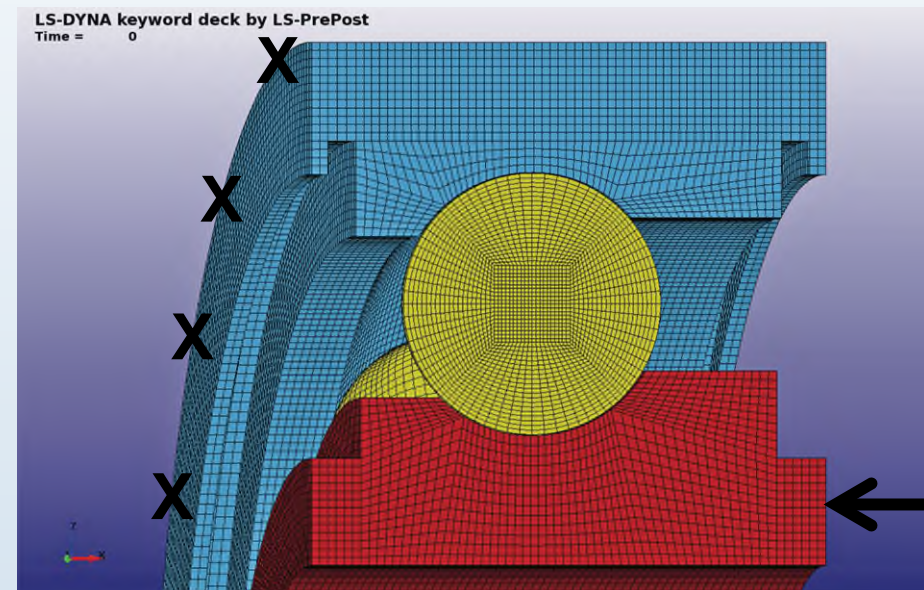
Solid model of the modified compressor bearing



Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

Modified bearing analyzed using LS DYNA:

- **LS DYNA Finite Element Model:**
 - Model includes inner race, outer race and balls (no cage).
 - Mesh using 8-node solid elements.
 - Outer race constrained in axial direction.
 - Inner race displaced axially toward outer race to simulate pressing force.
 - Balls are constrained in groove by way of a contact algorithm that applies penalty forces when nodes penetrate their opposing surface.



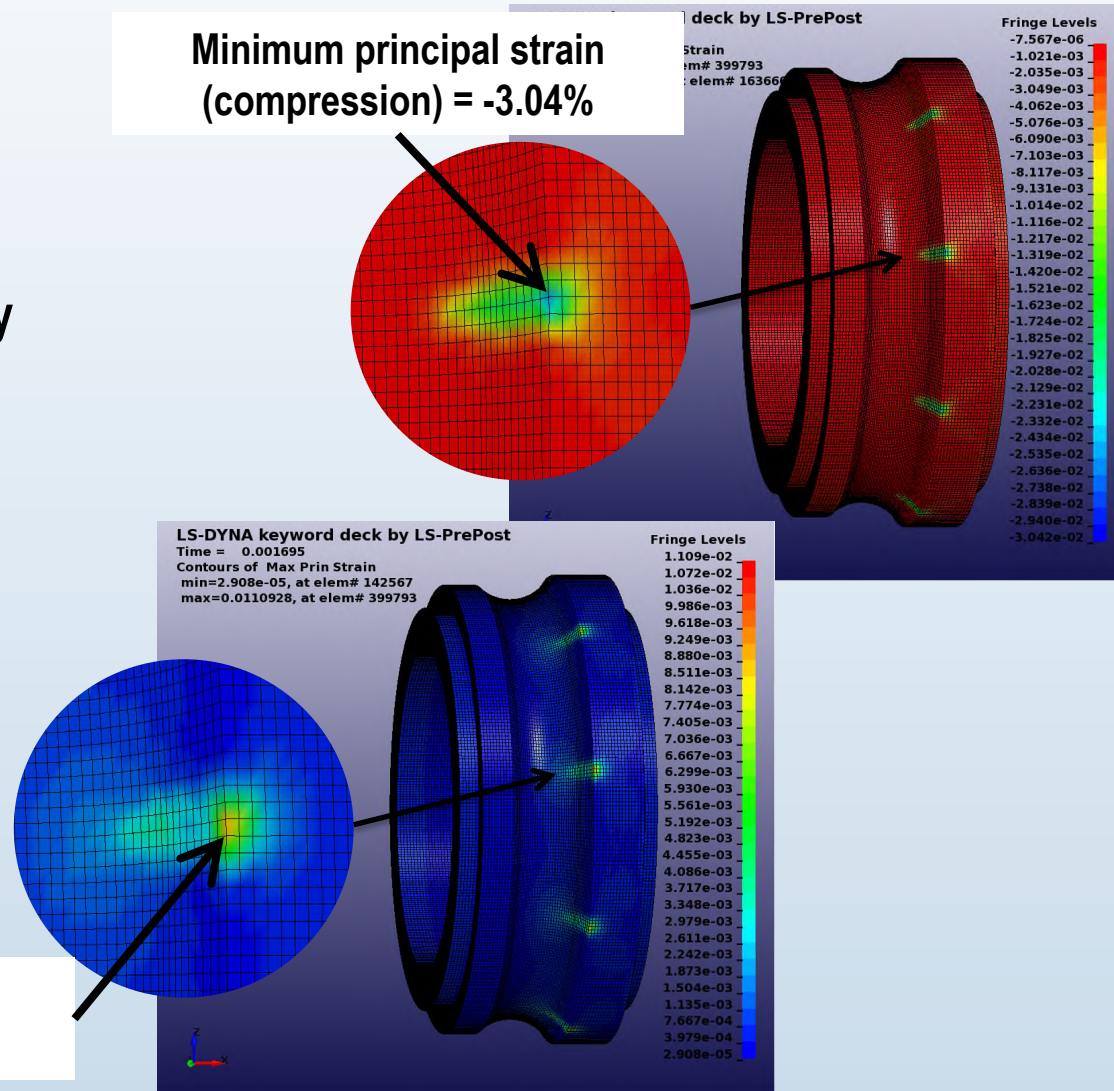
Mesh details for the modified compressor bearing



Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

Modified bearing analyzed using LS DYNA:

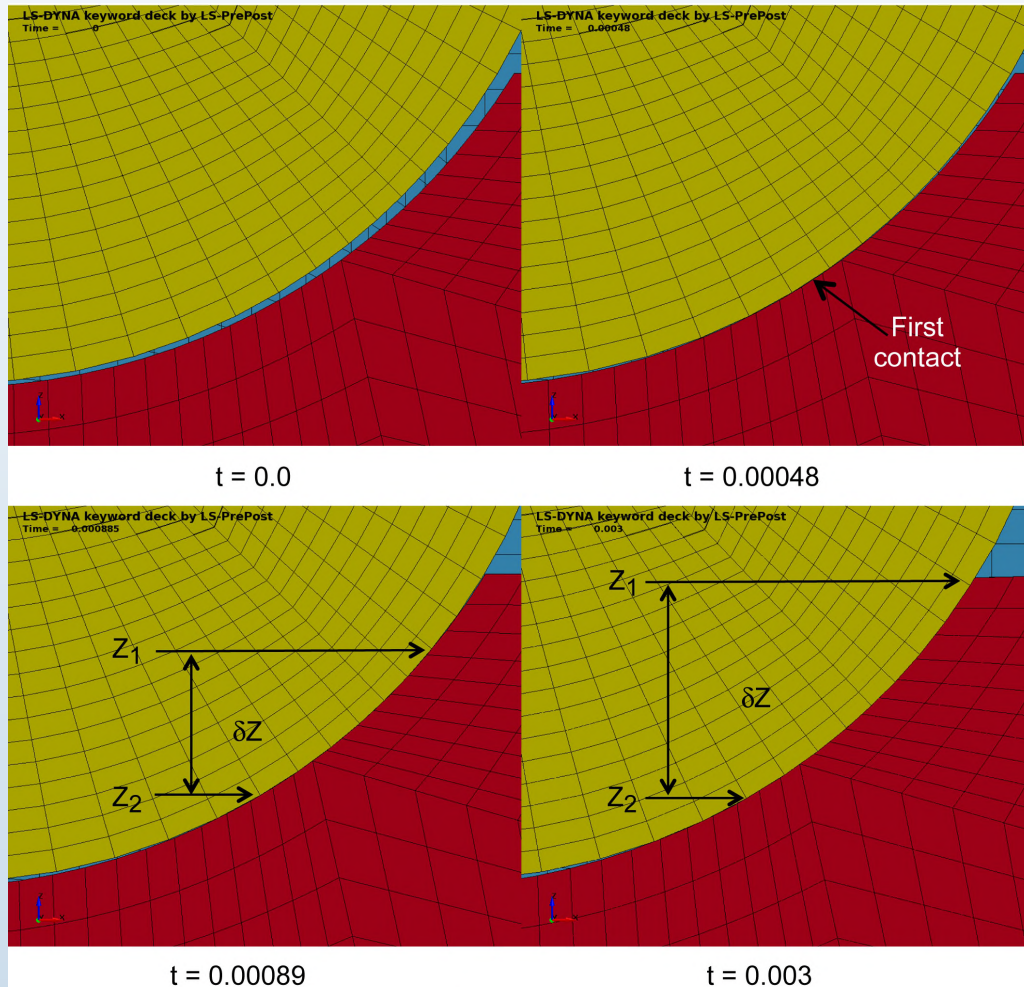
- Concern of material failure reduced:
 - Maximum and minimum principal strains predicted by DYNA:
 - 3.04% (compression)
 - 1.11% in (tension).
 - Both are less than fracture strain:
 - 9.45% (compression)
 - 1.45% (tension)
 - Not much margin in tension, but worst case loading.





Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

Modified bearing analyzed using LS DYNA:



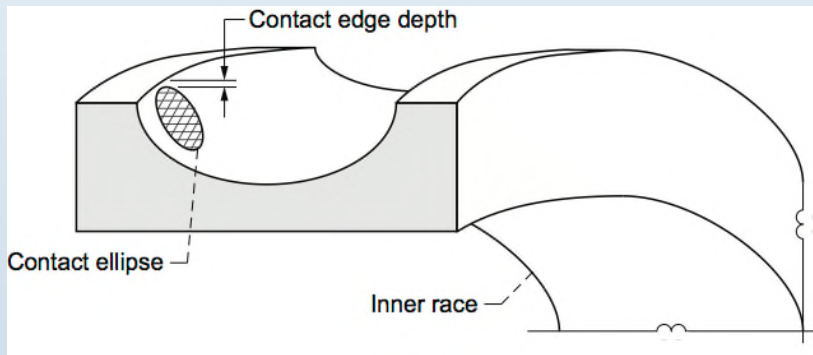
- However, new concern brought to light:
 - ADORE analysis predicted the balls would not roll over the edge of the groove.
 - But, LS DYNA analysis appears to suggest they do.
 - Difficult to determine where the edge of the contact is from a plot of strain or dynamic deformation plots... further analysis required to pinpoint limiting load.



Removable Superelastic Bearings: Detailed Design (LS DYNA bearing analysis)

Modified bearing analyzed using LS DYNA:

- A series of load case analyses are done to ascertain the load at which the contact reaches the groove edge.
 - To minimize the effects of dynamics, the analyses are extended to reach a pseudo steady-state condition.
 - Based on those simulations, the edge of the contact would just reach the edge of the groove when the axial load is 1.2 kN, and would exceed the edge of the groove at higher axial loads.



Contact edge depth = 0 at
1.2 kN axial load.

- LS DYNA result has uncovered a possible issue that was not seen (contradicted in) ADORE analysis.
 - Testing is planned to further investigate.

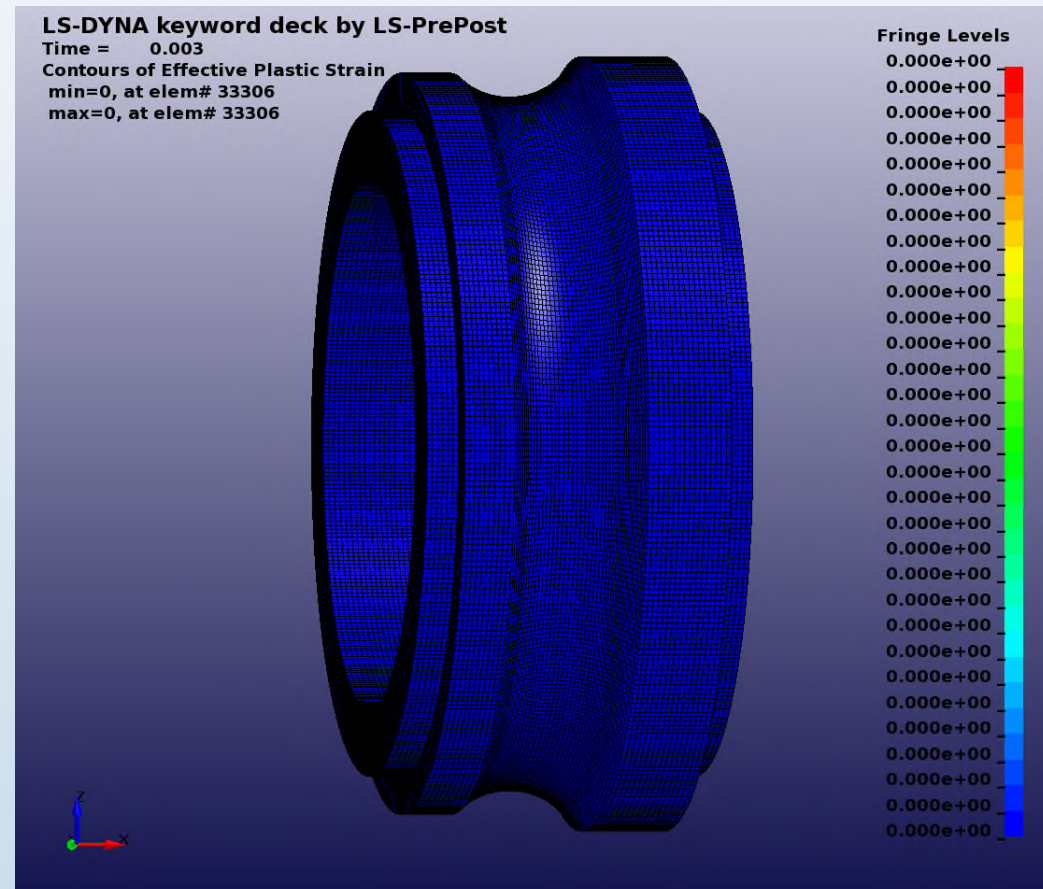


Modified bearing analyzed using LS DYNA:

- **No predicted plastic strain:**
Even with high strain peaks at the edge of the race grooves...

And, despite the balls rolling over the edge of the groove, there is no permanent deformation or failure, so may be acceptable?

Plastic strain





Summary Remarks: Part II Detailed Analysis

- **ISS DA Compressor bearing has been modified to take advantage of the beneficial hardness/superelasticity/corrosion resistance of 60NiTi.**
- **Lower contact stress and increased land heights increase the possibility of reusing compressor bearings after assembly/disassembly process.**
- **ADORE analysis predicts the bearing design will be robust from a contact stress and geometry perspective.**
- **LS DYNA analysis predicts no material failure (fracture) and no plastic strain (permanent deformation), although, in contrast to ADORE, does predict geometry may be an issue.**
- **An experimental test program on 60NiTi R8 ball bearings is currently underway to validate and supplement the modeling and analyses presented.**



Thank You!